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Morphostat: A simple beach profile monitoring tool for coastal zone management

T. Thomas[a,*], M.R. Phillips[a], A. Morgan[a], G. Lock[b]

[a] Coastal and Marine Research Group, University of Wales Trinity Saint David, Mount Pleasant, Swansea, Wales, SA1 6ED, UK
[b] Tidal Lagoon Power, Pillar & Lucy House, Merchants Rd, The Docks, Gloucester, GL2 5RG, UK

ABSTRACT

Tidal Lagoon Plc proposes UK-based construction of a hydro-electrical generating facility using the natural ebb and flow of the tide in Swansea Bay, South Wales. This will be the first of its type in the world and to verify its ecological footprint does not adversely affect the normal fluctuations of sediment in the bay, a regime was put in place to monitor potential intertidal morphological change before, during and post construction. An adaptive management strategy was developed to identify coastal changes outside normal evolutionary patterns and a baseline with a monitoring strategy to detect intertidal area change was developed from analysis of historic beach profile data collected between 1998 and 2013. The resulting profile envelope was utilised to define natural variation and evaluated against this was beach level data collected between 2015 and 2016. 'Morphostat', a novel application for monitoring beach level changes was developed to provide visual indication of areas of concern revealed from analysis against statistical parameters that is organised into tidal ladder regions. Users are also provided with a quantitative result that enables areas of concern to be identified and trigger levels to be defined. Morphostat visual output provides a traffic light system of Red, Amber and Green that identifies relative levels of concern. Here, exceedance of normal parameters will trigger higher levels of assessment against a predetermined management framework that would include forcing agents such as waves and storms etc. Although initially developed to monitor Swansea Bay, Morphostat can be applied elsewhere in the world for any tidal range, tidal ladder configuration and variable profile length, making it ideal as a first line tool to determine if more detailed assessments are needed. Morphostat is therefore a useful shoreline monitoring tool for underpinning intervention/no intervention policies. It will facilitate assessment of risk, especially from climate change, where beach change can be categorised as within or outside historical trends, thereby improving future high level strategic decision making, allocation of financial resources and coastal zone management, not only in the UK but on a more global scale.

1. Introduction

Monitoring beach profile change is a common and effective way of measuring erosion and accretion and these data are usually put in context by conceptual or generic models but these data are rarely used to inform coastal zone management (Phillips and Williams, 2007; Taveira Pinto et al., 2009). Cooper and Pilkey (2004) highlighted a comparative lack of understanding of the complexity of linking shoreline response to environmental forcing (including sea level rise). This is considered a major challenge for successful integrated coastal management, confounded by a lack of previous data (Granja, 2001; McLaughlin et al., 2002; Cooper and Pilkey, 2004; Phillips, 2008).

Suanez et al., (2009) argued that there is a need to explicitly incorporate realistic coastal processes and responses achieved by means of surveys. While, Komar (1998) highlighted the importance of the beach profile as a natural mechanism that causes waves to break and dissipate energy. Repeated measurement of its cross-sectional profile reveals: beach height, width, slope and volume; this data can be used to quantitatively establish beach response to storm events, recovery rates, and potential flood or erosion risk (see for example Carter, 1988; Carter and Woodroffe, 1994; Simm et al., 1996; Short, 1999; Pilkey et al., 2002; Phillips and Williams, 2007; Rogers et al., 2010 Thomas et al., 2014 and 2016). Since the seminal workings of Gornitz (1990) and Pethick (1996), coastal vulnerability index (VI) methodologies have been used to evaluate risk associated with sea level rise, storms, coastal inundation and erosion, see for example, Burzel et al. (2012), Rangel-Buitrago and Anfuso (2015), Boruff et al. (2005), and Aucelli et al. (2017).

* Corresponding author.
E-mail address: majella128@btinternet.com (T. Thomas).

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The use of variations in beach profiles is not new and research studies have utilised variations in beach profile to establish the health of a beach (i.e. Erosion/accretion rates) see for example Komar (1998) and Kamphius (2006) for theoretical interpretation and for practical applications local studies have been conducted by Short and Trembanis (2004); Phillips and Williams (2007); Thomas et al. (2011a,b, 2012a,b), inter-alia. Fenster et al. (1993) argued that an analyst must often compromise between accuracy with complex models and robustness of simpler ones. Statistical methodologies abound, (see for example, Winant et al., 1975; Douglas and Crowell, 2000; Aubrey et al., 1981, Phillips and Williams, 2007; Thomas et al., 2010, 2014, 2015).

This paper makes no attempt to attribute causal affects but utilizes beach profile data collected between 1998 and 2013 by Swansea and Carmarthen Bay Coastal Engineering Group (SCBCEG) and through data gathered from these profiles, the Morphostat programme established a baseline and monitoring strategy designed to detect changes in the intertidal areas between Mumbles (GR: 263150, 187250) and Sker Point (GR: 278800, 180200). The programme was originally developed to determine morphological change due to the construction of a tidal Lagoon, a hydro-electrical generating facility using the natural ebb and flow of the tide in Swansea Bay the first of its type in the world. But it can also be used in all coastal management programmes where suitable historic datasets exist. Statistically derived limits and results determine the extent of further examination if deemed necessary, thereby focusing limited resources in areas of most need.

2. Physical background

The Bristol Channel/Severn Estuary is an inlet from the Atlantic Ocean on the west coast of Great Britain, partially enclosed and separating Wales from England (Phillips & Crisp, 2010; Uncles, 2010; Thomas et al., 2015, Fig. 1a and b).

There are a number of large embayments along the margins of the outer Bristol Channel (Fig. 1c): Barnstable, Bridgewater, Swansea and Carmarthen (Thomas et al., 2016). Swansea embayment, located northwest Bristol, is a large sweeping, highly-indented and predominately sandy bay that can best be described as a crenulate shoreline, almost logarithmic in shape. Its tangential zone extends from Sker Point (GR 278604-179641) in the east, towards Margam and Baglan Burrows to the northwest, with a steadily decreasing radius within Swansea Bay and the spiral centre terminating at Mumbles promontory in the west (GR 263486-187161; Fig. 1c). The shoreline is approximately 29 km long, backed by either natural dune systems or retaining structures. It is a large industrial embayment, historically linked to the coal, steel and fishing industries with the main current industrial activity centred on Port Talbot. There is wider recreational use of the Bay focused at designated bathing beaches as well within the embayment. Therefore, positioning of a lagoon within this area requires careful consideration. Port Talbot Harbour and Swansea Dockland promontories with associated dredged channels interrupt longshore sediment drift, along with freshwater inputs from several rivers that flow into the inner bay, namely, the Rivers Tawe, Neath and Afan. The inner bay is generally shallow, particularly to the west but is deeper along the frontage of the west-southwest facing Baglan Burrows-Sker Point beach which is partially backed by extensive dune systems (Baglan and Kenfig Burrows respectively; Thomas et al., 2015). A veneer comprising of glacial sand and gravel covers Swansea Bay with underlying Carboniferous Limestone at Mumbles Head rising to 77 m AOD, contrasted against the rest of the coastline, which is low lying. Dominant and prevailing south-westerly winds that expose the Bristol Channel to unrefracted North Atlantic waves, ensure abundant wave action within these macrotidal 7.5 m spring tidal range waters (Phillips and Crisp, 2010). Offshore recorded south to westerly waves average 1.2 m height and 5.2 s period dominate, although storm waves > 5.5 m with periods > 8.5 s are not uncommon (Thomas et al., 2010, 2015; Rangel-Buitrago et al., 2016).

For ease of reporting, the natural (headlands and river out falls) and anthropogenic (harbours and sea defence structure) were used to modify profile groupings into a baseline sampling strategy that is defined by receptor areas (Table 1).

3. Methodology

3.1. Beach profile monitoring (1998–2013)

Swansea and Carmarthen Bay Coastal Engineering Group (SCBCEG) established twenty-nine evenly spaced beach profiles as a baseline for monitoring changes in the intertidal area between Mumbles and Sker Point (Fig. 2). In total, twenty-one surveys were conducted between 1998 and 2013. Representing 609 spatial and temporal datasets, i.e. *21 surveys x 29 profiles*. The profiles were of fixed origin and orientation, extending from above Highest Astronomical Tide (HAT) to around Mean Low Water of Neap Tide (MLWN). Initially surveys were carried out in spring and autumn of each year but from 2005 were limited to spring of each year (N.B. no surveys were conducted in 2011).

Ideally, management operations require knowledge of tidal elevations (i.e. Highest Astronomical Tide, High Water Mark Ordinary Spring Tide, etc.). These can be related to a suitable bench mark and used to establish beach face positions (see for example, SNH, 2000; Huang et al., 2002). Beach level variations were assessed between levels of fixed origin and the terminus of each profile irrespective of profile extent, as well as between a specified 'tide ladder', comprising standard tide level data derived from nearby tide gauges. Table 2 shows assignment of tide gauge data to profiles (reproduced from Barber, 2007). Many of the profile previous surveys only extended to around MLWN and the reasons for failure to survey the entire profile length are unclear but a pilot study conducted during spring 2015 did reveal some health and safety issues that may have contributed to this lack of data from the lower shore (i.e. profile length from foreshore, extensive areas of mud, sand banks/bars etc.).

3.2. Dataset comparisons

Historic dataset comparisons highlighted some differences in profile Control Point/Marker (CPM) position (x, y) and elevation (z), with the greatest difference being recorded in the earlier surveys. This is a consequence of technology advances in surveying equipment and techniques, particularly reflected in the change from more traditional total station equipment used for earlier surveys (assumed 1998–2004) to Real Time Kinematic (RTK) DGPS that was used on more recent surveys (2005–2013). Table 3 provides a statistical summary comparing control point coordinate values and corresponding differences between the 1998, 2005 and 2013 datasets. Ordnance Survey (OS) benchmarks were used to establish original CPM elevation values. Analysis showed that except for profiles T215, T217 and T227, most 2005 CPM elevation values were lower than their corresponding 1998 values, with average differences of −0.202 m within the range 0.573 m and −0.572 m (Table 3). Corresponding differences in eastings averaged −0.412 m, ranging between −6.620 m and 2.374 m, while Northing differences averaged 0.246 m, ranging between −5.049 m and as much as 11.622 m. DGPS surveys carried out between 2005 and 2013 showed very small variations that averaged as follows: 0.004 m (easting), 0.003 m (northing) and 0.012 m (elevation). Unsurprisingly, elevation differences between 1998 and 2013 were similar to those found between 1998 and 2005 although two control points proved an exception, i.e. T226 (1.520 m) and T228 (−1.431 m).

3.3. Data transformation

It was important that the 1998–2013 dataset was standardized and surveying errors minimized. However, it had to be assumed that there were no random or systematic errors generated with the total station

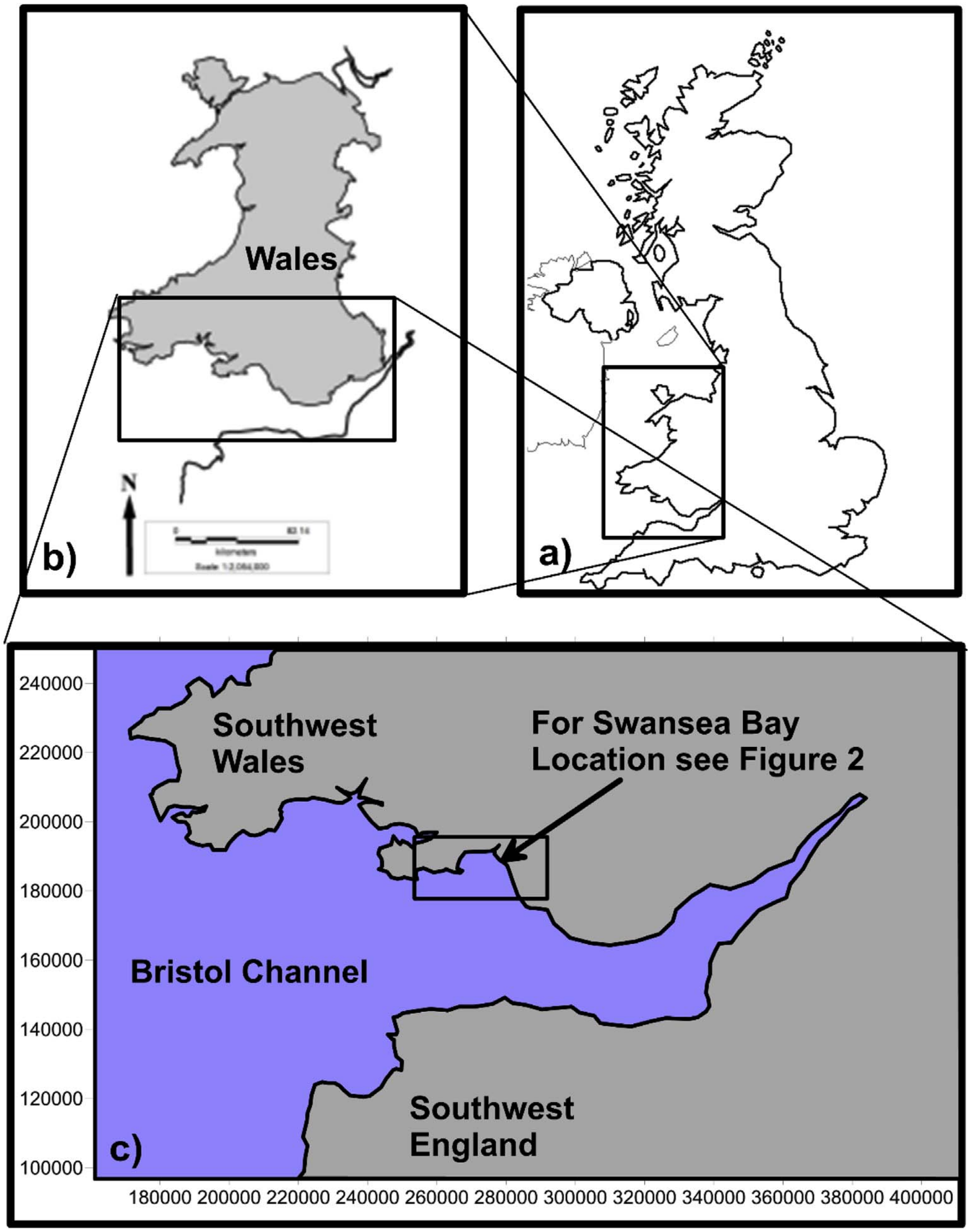


Fig. 1. Locality of the study area, a) United Kingdom, b) Wales and southwest England and c) Bristol Channel and the southwest English and Welsh coastlines.

Table 1
Receptor and associated transects.

Receptor	Transect range
Mumbles and Blackpill SSSI	T201 – T207
Swansea Beach	T208 – T210
Lagoon footprint	T213 – T214
Crymlyn Burrows SSSI	T215 – T216
Baglan Burrows	T217 – T218
Aberavon Sands	T219 – T221A
Margam Sands	T223 – T227
Kenfig SAC	T228 – T230A

surveys (1998–2005). The surveying equipment was set accurately over each Control Point Marker (CPM) and the height of collimation (instrument height) was determined in relation to given CPM elevation values, that the survey origins (CPM's) were correctly set at zero and distances along each profile are relative. CPM co-ordinate and elevation values relate to original ground position and that any discrepancies found in later datasets were relative to that point. Finally, the survey results for 2013 were accepted as correct and therefore suitable as baseline data from which all errors were transformed.

Elevation errors were eliminated by calculating differences between the baseline survey and earlier CPMs. This difference was then applied to each survey point along a given profile. The efficiency of this transformation is best demonstrated using beach profile T203 where a variance of 0.262 m was found between the 2013 baseline CPM level (6.360 m AOD) and the 2003 value (6.622 m AOD). The 0.262 m variance was subtracted from each level along the entire spring 2003 profile to compensate for the discrepancy. Fig. 3 clearly shows the benefit of applying these adjustments to profile T203 where original survey elevations (Red line) were too high but following corrections for the 0.262 m variance, elevations more closely follow those surveyed in 2013 (Blue line).

Working on the supposition that CPM Position was correctly located on all previous surveys and that the most recent survey (2013) value was correct, any discrepancies would be relative to the most recent survey. Therefore, previous datasets were adjusted using the 2013 CPM

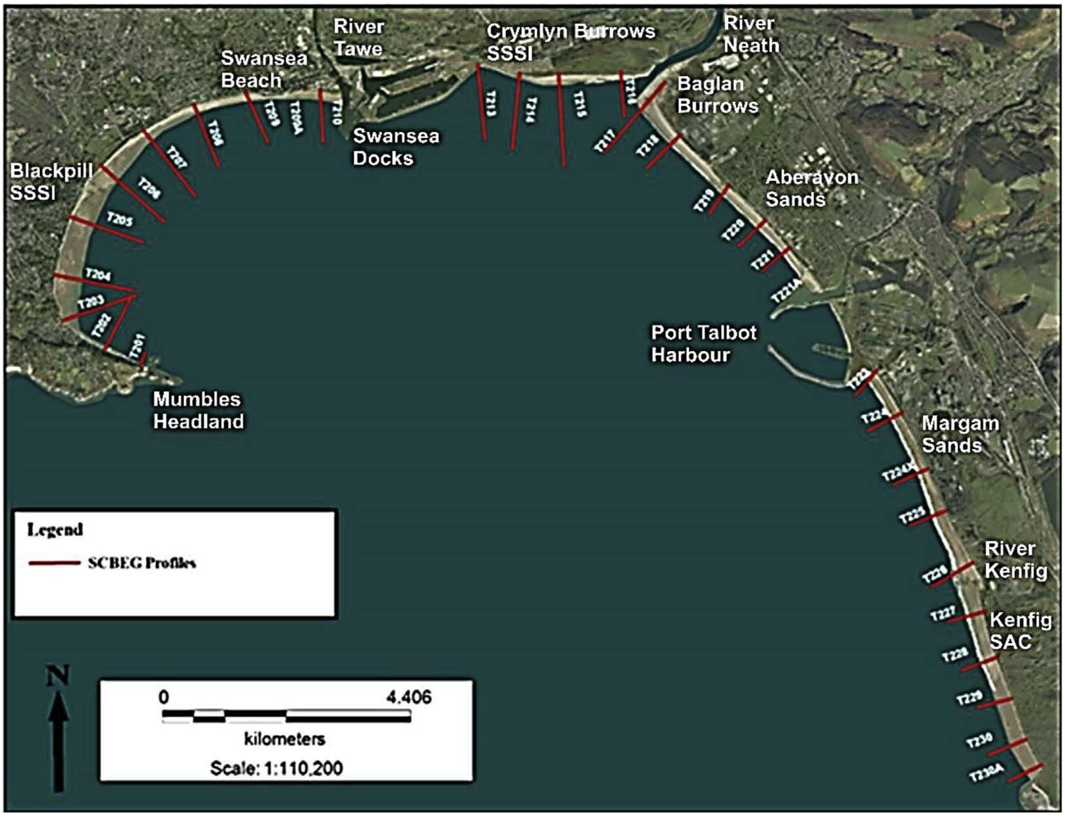


Fig. 2. Aerial photograph (2010) depicting Swansea Bay beach profile locations.

Table 2
Tide gauge data and beach profile allocations reproduced from Barber (2007).

Established tide locations	Tide values	
	Mumbles	Aberavon
Highest Astronomical Tide (HAT)	5.2	5.2
Mean High Water Spring Tides (MHWS)	4.1	4.3
Mean High Water (MHW)	3.1	3.2
Mean High Water Neap Tide (MHWN)	2.1	2.1
Mean Sea Level (MSL)	0.0	0.1
Mean Low Water Neap Tide (MLWN)	−1.7	−1.8
Mean Low Water (MLW)	−2.8	−3.0
Mean Low Water Spring Tides (MLWS)	−4.1	−4.1
Profile tide gauge distribution	T201-T216	T217-T230A

value as a baseline position fix. Profile line Whole Circle Bearings (WCBs) were also recalculated using 2013 CPM co-ordinates (E_{zero}/N_{zero}) and furthest seaward position fix (E_{end}/N_{end}) using equation (1). It is worth noting that WCB results were almost identical to those used in all previous surveys. Subsequently, 2013 CPM co-ordinates (E_{zero}/N_{zero}) and calculated WCBs were used with respective profile distances (D) to compute new co-ordinate values (E_{calc} and N_{calc}) along each profile, using equations (2) and (3) respectively.

$$WCB = \tan^{-1}[(E_{end} - E_{zero}) / (N_{end} - N_{zero})] \tag{1}$$

$$E_{calc} = [E_{zero} + (D\sin(WCB)] \tag{2}$$

$$N_{calc} = [N_{zero} + (D\cos(WCB)] \tag{3}$$

The efficiency of this transformation is also best demonstrated using beach profile T215 as an example, Fig. 4a displays graphically the horizontal difference between original and adjusted datasets. Here a red line represents original coordinate data points that required transformation while a black line denotes these same data points, processed to align with 2013 baseline levels and co-ordinates (blue dots). Fig. 4b displays graphically the vertical difference between the original and adjusted datasets similarly, the red line represents original offset (from the CPM) and vertical data points that required transformation while a black line denotes these same data points, processed to align with 2013 baseline levels (blue dots).

3.4. Beach profile monitoring (2015–2016)

Two surveys along the existing SCBCEG profiles were conducted in Autumn (2015) and Spring 2016 using GPS equipment to achieve horizontal and vertical control This involved use of GNSS with data derived directly from the OS Net. Similar to RGA surveys, the horizontal

Table 3
Summary maximum, minimum and average differences.

	Differences 1998–2005			Differences 2005–2013			Differences 1998–2013		
	East	North	Level	East	North	Level	East	North	Level
Maximum	2.374	11.622	0.573	0.100	0.117	1.520	2.370	11.618	1.338
Average	−0.412	0.246	−0.202	0.004	0.003	0.012	−0.402	0.240	−0.189
Minimum	−6.620	−5.049	−0.572	−0.004	−0.005	−1.431	−6.620	−5.047	−1.969

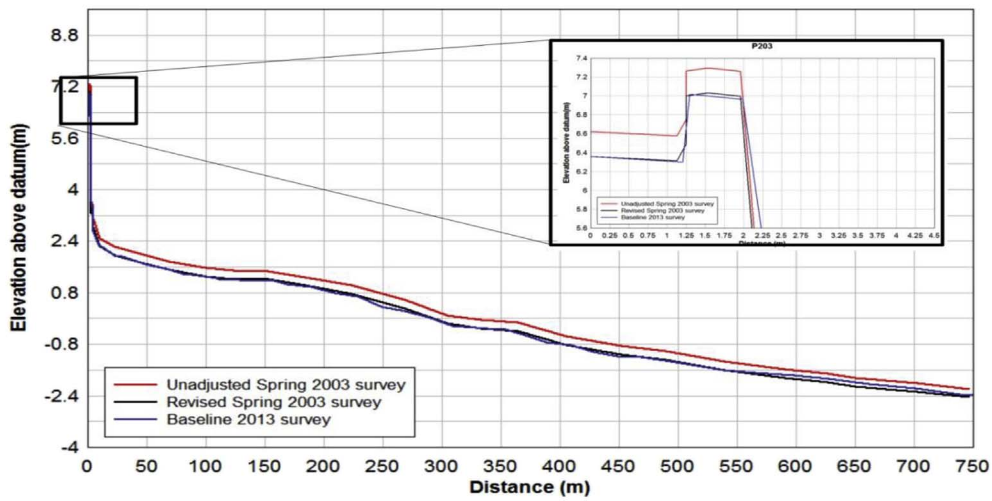


Fig. 3. Pre/post transformation of spring 2003 elevations, alongside baseline 2013 survey.

and vertical control was achieved using GNSS with data derived directly from the OS Net. Equipment comprised a Geomax Zenith 25 receiver, capable of acquiring data horizontally at ± 10 mm 1 ppm (rms) and vertically at 20 mm ± 1 ppm (rms), and a Getec touchpad tablet containing X-Pad surveying software was used to acquire data. The Zenith receiver, housing a SIM card and employing Q-lock satellite tracking technology was mounted on top of a 2 m pole.

3.5. Data analysis

Beach level data for each profile was imported into Regional Morphology Analysis Package (RMAP). This comprises an integrated set of automated and interactive tools to analyse morphologic and dynamic properties of shoreline data and beach profiles, (see Morang et al., 2009 for theoretical approaches and Thomas et al., 2011a,b, Thomas et al., 2012a,b and Thomas et al., 2015 for practical applications). Data was truncated to the control point (zero chainage), interpolated at a standard chainage (in this case 5 m) along each profile and downloaded in comma separated values format for further investigation. Subsequently, these data were input into the 'Morphostat' programme; 'Morphostat', developed by the University of Wales Trinity Saint David, is a novel application for monitoring beach level changes. Developed to provide a visual indication of areas of concern revealed from analysis against statistical parameters that is organised into tidal ladder zones. The programme comprises of a semi-automated set of tools designed to identify changes inside and outside-statistically derived confidence limits, constructed around the individual beach profile envelope.

Users are provided with a quantitative result of the determined changes within individual tidal ladder contours, enabling areas of concern to be identified and trigger levels to be defined, displayed visually by a traffic light system of Red, Amber and Green. The programme also provides an overall summary of profile condition in relation to predetermined trigger levels also displaying the results in a traffic light system for easy identification. Exceedance of normal parameters will trigger higher levels of assessment against a predetermined management framework that would include an assessment of forcing agents such as variations of in-wave height and direction, storm and surge incidence etc.

4. Development of an adaptive monitoring plan

4.1. Trigger levels

Intertidal change was assessed using appropriate quantifiable trigger levels established from analysis of the historic survey dataset. From this, trigger levels to monitor and assess beach morphology changes were developed. Any change to profile levels that exceed those identified through analysis of 1998–2013 SCBCEG data (i.e. the historic baseline) were considered to have fallen outside normal natural variation for that profile. The results of the assessment against trigger levels is then reported by means of a traffic light system of red, amber and green as discussed below and such changes in beach morphology will act as a trigger for further action.

There is generally an expectation that significant 'in-transect' variation of beach levels would be observed at many locations, particularly when consideration is given to the temporal scale of the present dataset and this phenomenon can be caused by presence of features such as a migrating sandbar. Here, material that can migrate along a profile will be reported as exceeding the trigger even though this is a natural process in operation. As mentioned above, a trigger level framework is used to detect change in the intertidal area, with a traffic light system highlighting areas of concern and thereby identify the need for action where necessary. This traffic light system and associated action required is set out below in Table 4.

4.2. Beach profile change trigger level

Ideally, thresholds used to assess potential change on beaches should be based upon variations in beach level and/or volume. The 1998–2013 historic beach profile dataset provides a good baseline from which to assess potential change. However, a particular challenge was that length variations of baseline profiles restrict the amount of data that could provide input into any proposed model, as data would have to be truncated to the closest contour. To address this challenge the Morphostat programme was developed. Essentially, the beach profile envelope was utilised to develop a statistical approach that maximises the profile length despite variations in profile length. The following steps have been used to achieve this aim:

1. Individual profile data was interpolated at 5 m intervals within RMAP software and subsequently imported into the Morphostat programme.
2. Morphostat calculates the average, maximum, minimum and standard deviation (SD) for each transect.
3. Confidence intervals based on 95%ile (± 1.96 SD) and 99%ile (± 2.33 SD) is also calculated for either side of 'average'.
4. Identified confidence intervals are colour coded for ease of reference, as shown in Table 5 (subsequent survey data will be reviewed against set baseline Confidence Intervals).
5. Data was divided into intertidal zones e.g. HAT to MHWS, etc.
6. For each profile, the percentage of green values allocated to trigger exceedance was determined by the actual percentage of levels for

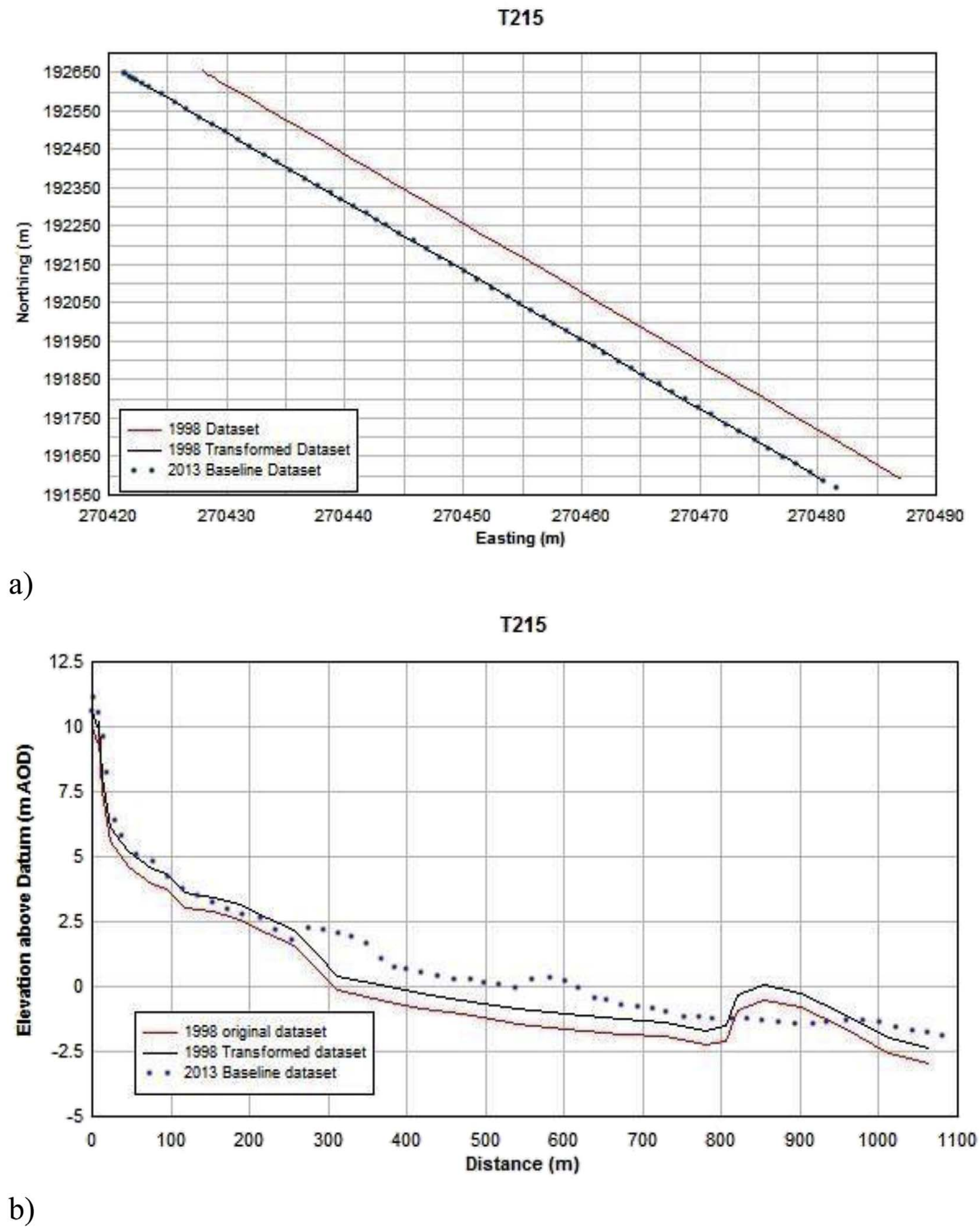


Fig. 4. a) T215 horizontal transformation (autumn 1998) b) T215 vertical transformation (autumn 1998).

that profile that were calculated green using data from the Autumn 2015 survey.

5. Results

5.1. Application of beach level confidence intervals

To show the efficacy of the Morphostat programme there follows an analysis of the survey results from Autumn (2015) and Spring 2016, compared with the 1998–2013 historic dataset for two example profiles (T207 and T2015).

5.1.1. Analysis of autumn (2015) data for T207 and T215

Fig. 5 shows an illustration of T207 (Blackpill SSSI), with Fig. 5a showing all data collected over the period 1998–2013 and Fig. 5b showing Autumn 2015 data and the respective confidence intervals (based on the historic dataset). Fig. 6 displays similar data for T215 (Crymlyn Burrows SSSI).

Fig. 7 (taken from Morphostat) summarises the Autumn 2015 colour-coded results for the relevant tidal ladder zones of each transect, suitably annotated to depict direction of change where appropriate. Based upon profile stability, green exceedance trigger levels were set at 84.62% for T207 and 89.9% for T215 using the percentage of levels not exceeding the confidence intervals during the Autumn 2015 survey (i.e. those levels reported as ‘green’ and therefore reflecting natural variation for that transect).

Fig. 5b (lower panel), shows that T207 for the most part remained within green status (within 95%ile). However, while it was found to be stable along most of its length, two sections did go outside the 99%ile trigger level (MHWN-MSL and MSL-MLWN) and this concurred with

Table 4
Trigger level framework.

Category	Definition
Change within acceptable limit	The monitoring shows that response of the receptor is within the defined envelope of baseline variation. Monitoring will continue and no further action is required
Temporary or isolated change	The monitoring shows that response of the receptor is above or below baseline natural variation in a given timescale, and if this trend continued, could be of concern.
Excessive, persistent and/or repeated change	The monitoring shows that response of the receptor is at a magnitude outside baseline natural variation and/or is persistent/repeated. Further action may be required and analysis of supporting data will be undertaken.

Table 5
Zones for beach change confidence intervals.

Green	Amber	Red
<95%ile	>95%ile but < 99%ile	>99%ile

Fig. 7 results (Individual Tidal Ladder Status). In this Figure, it can be seen that in tidal ladder zone MHWN – MSL, the percentage that remained within green status was 71.88% which is below the allocated exceedance limit of 84.62%. The second tidal ladder zone, MSL to MLWN, only achieved 60.47% in green status (again below the 84.62% threshold).

For the upper tidal ladder zone, there was a resultant higher percentage in the 'Red Increase' section and so this zone was allocated a status of 'Red Increase'. For the adjacent tidal ladder zone (MSL to MLWN) an equal number of Amber and Red decreasing were recorded and as such the Red decreasing status was allocated.

Notwithstanding this, the 'overall profile status' remained 'Green' status since the profiles' total green levels was equal to the 84.62% threshold. On further examination of the shape of the historic beach profile change (Fig. 5a top panel) and the confidence intervals (Fig. 5b lower panel), it is evident that presence of a sand bank moving further up the beach has affected the results. Overall assessment suggests this profile was relatively stable and mostly remained within the bounds of statistical confidence.

Fig. 8 (taken from Morphostat) also summarises the Autumn 2015 colour-coded results for the relevant tidal ladder zones of each transect, suitably annotated to depict direction of change where appropriate. Based upon profile stability, green exceedance trigger levels were set 89.9% for T215 using the percentage of levels not exceeding the confidence intervals during the Autumn 2015 survey (i.e. those levels reported as 'green' and therefore reflecting natural variation for that transect).

T215 was also mainly green (within 95%ile), as shown in Fig. 6b (lower panel). Most individual tidal ladder zones remained at green status by achieving the 89.9% requirement. However, three sections did fall within the 95%ile and 99%ile trigger levels, namely, Origin-HAT and MHWS-MHWN (two zones) and once again this concurred with table results (Fig. 8). In this table, it can be seen that the percentage of Origin-MHWS that achieved green status was 33.33%, which was below the allocated exceedance limit of 89.9% with the remaining results being amber (25.00%) and red (41.67%) and so this zone was allocated a status of 'Red Increase'. The percentage of MHWS-MHW that remained green status was 78.95%, which was slightly below the allocated exceedance limit, with the remaining results being amber (21.00%) and so this zone was allocated a status of 'Amber Increase'. In the adjacent zone (MHW-MHWN) no levels achieved green status with the remaining results being amber (58.33%) and red (41.67%) and so this zone was also allocated a status of 'Amber Increase'.

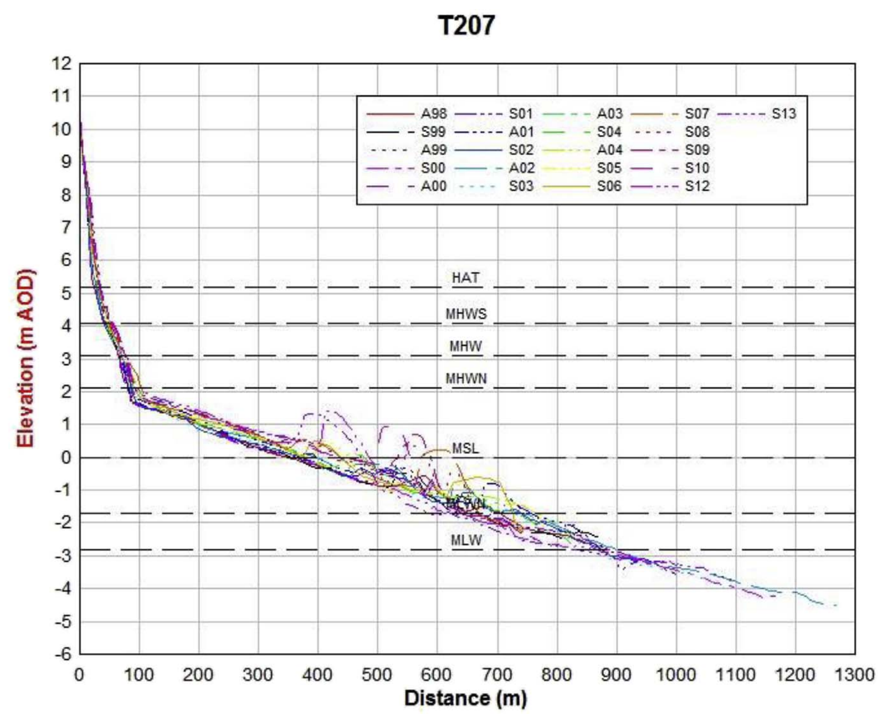
5.2. Analysis of spring (2016) data for T207 and T215

As presented above, the Autumn 2015 data was assessed against the confidence intervals determined through analysis of the historic data set. From this the profile stability, which reflects the transects natural variation, was also determined. The confidence intervals from the historic dataset and the 'profile stability' from the Autumn 2015 analysis has been used in the following section to assess the Spring 2016 data for T207 and T215.

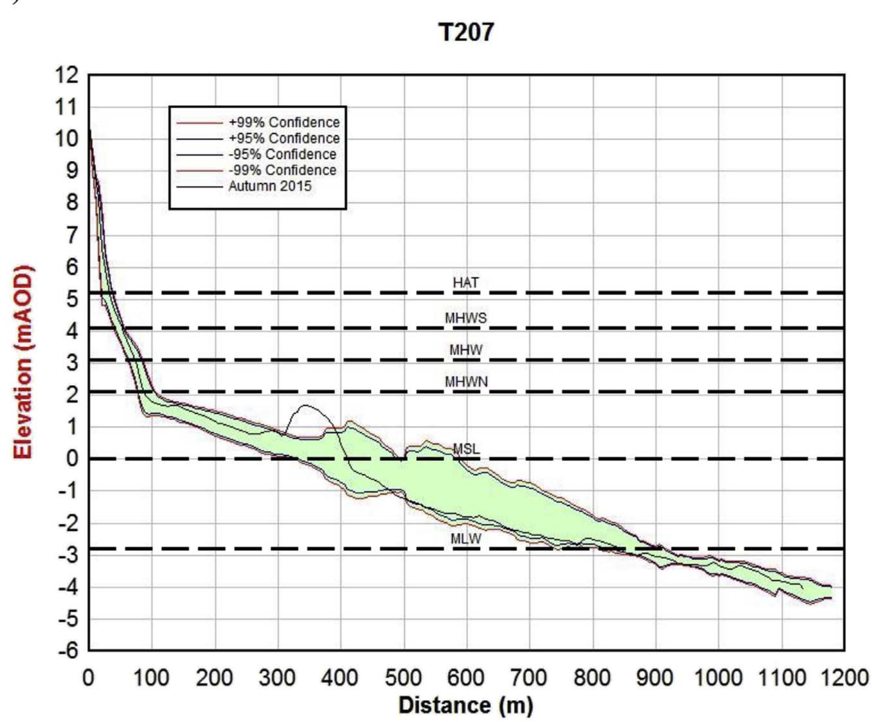
Fig. 9 shows an illustration of the Spring 2016 data with respective confidence intervals (based on the historic data set, 1998–2013) for T207 (Blackpill SSSI) (top panel) and T215 (Crymlyn Burrows SSSI) (lower panel).

Fig. 10 (taken from Morphostat) summarises the Spring 2016 data set for each transect, colour-coded for the relevant tidal zones of each transect, and suitably annotated to depict direction of change where appropriate. As found in the previous survey, Fig. 9a shows that T207 for the most part remained within green status (within 95%ile). However, while it was found to be stable along most of its length, two adjacent tidal ladder zones did fall outside the 95% or 99% trigger level, namely MHWN – MSL and MSL to MLWN and this concurs with Fig. 10 results (Individual Tidal Ladder Status). In this Figure, it can be seen that in tidal ladder zone MHWN – MSL the percentage that remained within green status was 71.43%, which is below the allocated exceedance limit of 83.54%. For this tidal ladder zone, there was a resultant higher percentage in the 'Red Increase' section (26.90%) and so the tidal ladder zone was allocated a status of Red Increase. As with the Autumn 2015 data, the tidal ladder area below was showing erosion as opposed to accretion. Here, there were 59.38% within Green status, with the remaining results being Amber (25%) and Red (15.63%). The tidal ladder zone was allocated a status of Amber decrease. Looking at the Profile as a whole, 79.04% remained within green status, which is below the 84.62% threshold. Overall 7.19% were decreasing Amber, 10.1% were increasing Red. As such, the overall profile status was Red Increase. On further examination of the shape of the beach profile (Fig. 9a) it is evident that the sandbank noted moving up the beach in Autumn (2015) has continued this up tide migration, taking the dataset outside that previously recorded.

Fig. 11 (taken from Morphostat) also summarises the Spring 2016 data set for each transect, colour-coded for the relevant tidal zones of each transect, and suitably annotated to depict direction of change where appropriate. Fig. 9b shows that T215 was outside the 99% confidence limit for the tidal zone ORIGIN to HAT, with 84.62% being



a)



b)

Fig. 5. a) T207 beach profiles 1998–2013 and b) confidence intervals alongside morphological zones with autumn 2015 data (solid line).

in the Red. Further down the profile, at two adjacent tidal ladder zones (MHWS-MHW and MHW-MHWN) the number of levels remaining within green status had reduced from the autumn 2015 with 75% and 0% respectively. The remaining beach levels in these areas rose above 95%ile and 99%ile limits and both tidal ladder zones were allocated an overall Red status. Overall T215 was allocated a Red Increase status with the percentage green below the trigger value of 89.9%, and with 8.7% of the beach levels as increasing red. Looking at Fig. 9b, whilst T207 exceedance was a result of migration of a distinct sandbank, T215 exceedance appear to be associated with more subtle accretion within the relevant tidal zones.

5.3. Overall morphostat assessment of Swansea Bay

Table 6 summarises Morphostat results for profile locations T201 to T210, reflecting changes between defined tidal ladder contours with ↑ or ↓ indicating the general direction of beach level movement. The Mumbles and Blackpill SSSI (T201-T207) profiles have remained

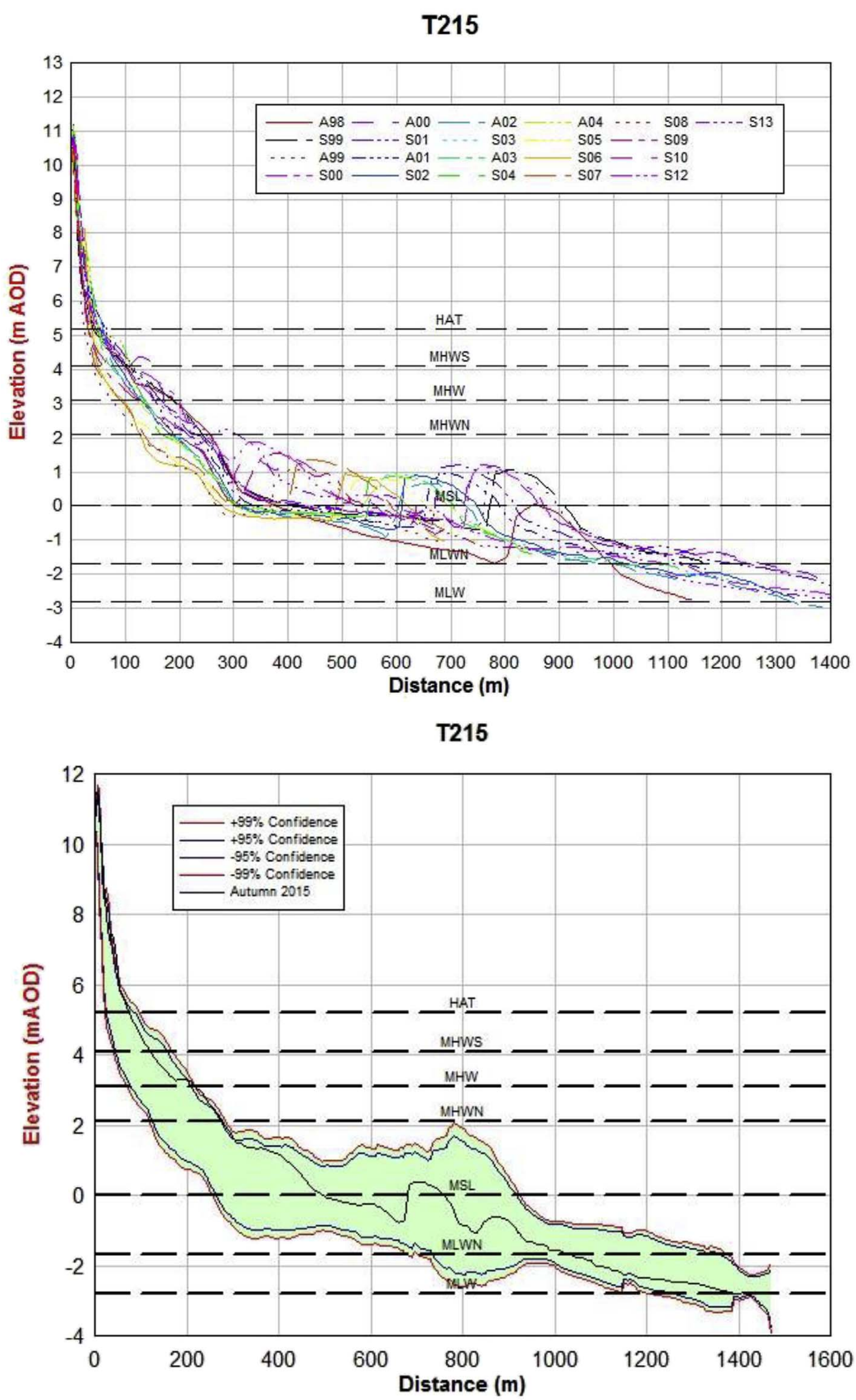


Fig. 6. a) T215 beach profiles 1998–2013 and b) confidence intervals alongside morphological zones with autumn 2015 data (solid line).

relatively stable with 69.39% of the assessed tidal ladder zones allocated green status with the remaining results being amber (4.08%) and red (26.53%). Two zones that fell below the 99%ile confidence limit were associated with the area between the Origin (CPM) and HAT. In this area, the upper and lower confidence limits converge and slight variations (within the confines of equipment accuracy) can influence results. It can be seen that overall, three profiles exceeded the 99%ile exceedance limit and as such, will require further assessment. While Swansea Beach (T208-T210) profiles show evidence of change in the supratidal and intertidal area, at T208. Here, continued shoreline migration of a sandbank within the upper tidal area highlighted in the previous report. The T209 profile has mostly remained within the exceedance limits but T210 shows evidence of level differences that rise above the recorded averages and Autumn 2015 data. Only 42.86% of the assessed tidal ladder zones were allocated green status with the remaining results being increasing amber (4.76%) and red (52.38%). Two zones that fell below the 99%ile confidence limit were associated with the area between the Origin (CPM) and HAT. In this area, the upper and lower confidence limits converge and slight variations (within the confines of equipment accuracy) can influence results. The zones that rose above the 99%ile confidence limit were mostly located between MHWS and MSL. The origins and cause of the changes within

Input Your Chosen "Green" Percentage Trigger Here [a]						84.62%	Profile T207 Autumn 2015 (Confidence Levels based on surveys between 1998 and 2013)
Tidal Ladder	RED (Increase)	AMBER (Increase)	GREEN	AMBER (Decrease)	RED (Decrease)	Total Levels	Individual Tidal Ladder Status:
ORIGIN To HAT	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
10.43 To 5.2	0	0	7	0	0	7	
HAT To MHWS	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
5.2 To 4.1	0	0	4	0	0	4	
MHWS To MHW	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
4.1 To 3.1	0	0	4	0	0	4	
MHW To MHWN	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
3.1 To 2.1	0	0	3	0	0	3	
MHWN To MSL	23.44%	4.69%	71.88%	0.00%	0.00%	100.00%	Status is Red Increase
2.1 To 0	15	3	46	0	0	64	
MSL To MLWN	0.00%	0.00%	76.47%	11.76%	11.76%	100.00%	Status is Red Decrease
0 To -1.7	0	0	26	4	4	34	
MLWN To MLW	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
-1.7 To -2.8	0	0	53	0	0	53	
Totals	15	3	143	4	4	169	Profile T207 Autumn 2015 Overall profile Status:
	8.88%	1.78%	84.62%	2.37%	2.37%	100.00%	Status is Green

Fig. 7. Morphostat assessment of the T207 example profile for Autumn 2015.

this receptor are unclear but anthropogenic influence in the form of dune management may be a contributory factor. It can be seen that overall, two profiles exceeded 99%ile exceedance limits.

Table 7 also summarises Morphostat results for profile locations T213 to T221. Here, the Lagoon Footprint profiles (T213-T214) remained relatively stable and 57.14% of the tidal ladder zones achieved green status, with the remaining results being amber (14.29%) and red (28.57%). The zones that fell below the 99%ile confidence limit were associated with the area between the Origin (CPM) and HAT. In this area, the upper and lower confidence limits converge and slight variations (within the confines of equipment accuracy) can influence results. It can be seen that overall, both profiles exceeded the allocated 95%ile or 99%ile trigger levels and, as such, will require further assessment.

Crymlyn Burrows SSSI (T215-T216) profiles have remained relatively stable with 71.43% of the assessed tidal ladder zones allocated green status, and the remaining result red (28.57%). Two zones that rose above the 99%ile confidence limit (14.29%) were associated with the area between the Origin (CPM) and HAT. In this area, the upper and lower confidence limits converge and slight variations (within the confines of equipment accuracy) can influence results. It can be seen that overall, one profile (T215) exceeded the allocated 99%ile trigger levels and, as such, will require further assessment.

Results show the Baglan Burrows (T217-T218) profiles have remained relatively stable with 78.57% of the assessed tidal ladder zones allocated green status, with the remaining results being amber (14.29%) and red (7.14%). It can be seen that overall, both profiles remained within the allocated 95%ile trigger levels and will not require

Input Your Chosen "Green" Percentage Trigger Here [a]						89.9%	Profile T215 Autumn 2015 (Confidence Levels based on surveys between 1998 and 2013)
Tidal Ladder	RED (Increase)	AMBER (Increase)	GREEN	AMBER (Decrease)	RED (Decrease)	Total Levels	Individual Tidal Ladder Status:
ORIGIN To HAT	41.67%	25.00%	33.33%	0.00%	0.00%	100.00%	Status is Red Increase
10.566 To 5.2	5	3	4	0	0	12	
HAT To MHWS	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
5.2 To 4.1	0	0	10	0	0	10	
MHWS To MHW	0.00%	21.05%	78.95%	0.00%	0.00%	100.00%	Status is Amber Increase
4.1 To 3.1	0	4	15	0	0	19	
MHW To MHWN	41.67%	58.33%	0.00%	0.00%	0.00%	100.00%	Status is Amber Increase
3.1 To 2.1	5	7	0	0	0	12	
MHWN To MSL	0.00%	8.47%	91.53%	0.00%	0.00%	100.00%	Status is Green
2.1 To 0	0	5	54	0	0	59	
MSL To MLWN	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
0 To -1.7	0	0	92	0	0	92	
MLWN To MLW	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
-1.7 To -2.8	0	0	83	0	0	83	
Totals	10	19	258	0	0	287	Profile T215 Autumn 2015 Overall profile Status:
	3.48%	6.62%	89.90%	0.00%	0.00%	100.00%	Status is Green

Fig. 8. Morphostat assessment of the T215 example profile for Autumn 2015.

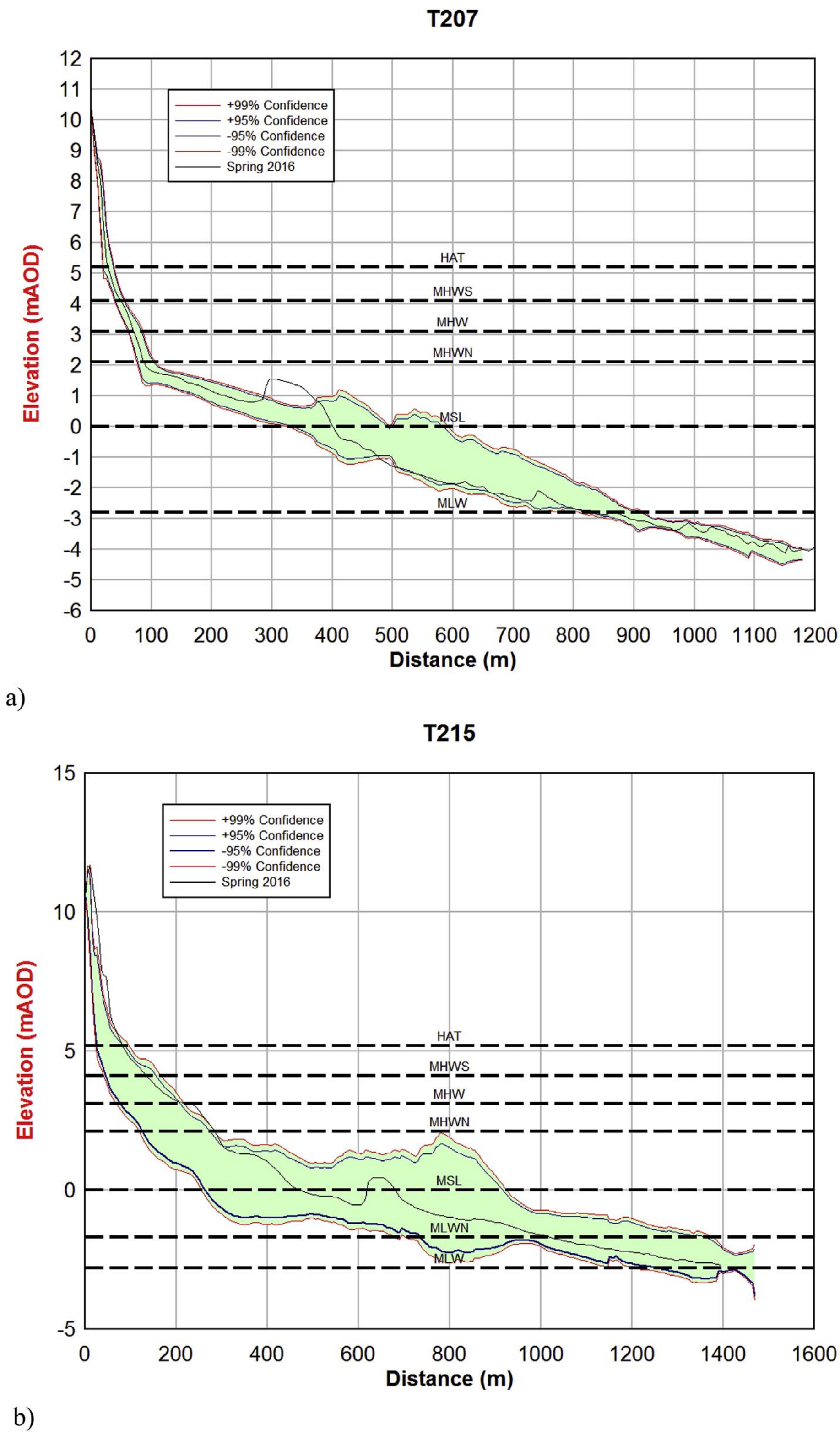


Fig. 9. Spring 2016 data from a) T207 and b) T215 with confidence intervals alongside morphological zones.

further investigation.

Looking at Aberavon Sands (T219-T221) as a whole, 78.57% of the assessed tidal ladder zones were allocated green status, with the remaining results being amber (7.14%) and red (14.29%). Four of the zones that fell outside the 99%ile allocated exceedance limits (28.56%) were associated either with the area between the Origin (CPM) and HAT or the area between HAT and MHW (i.e. the control point or sea defence). In these areas, the upper and lower confidence limits converge and slight variations (within the confines of equipment accuracy) can influence results.

Table 8 results highlight that Margam Sands (T223-T226) profiles have varied with 51.43% of the assessed tidal ladder zones allocated green status, and the remaining results being amber (5.71%) and red (42.86%). However, five zones that fell outside the 99%ile confidence limit (17.143%) were associated with the area between the Origin (CPM) and MHWS. In this area (located on or landward of the sea

Input Your Chosen "Green" Percentage Trigger Here			84.62%				Profile T207 Spring 2016 (Confidence Levels based on surveys between 1998 and 2013)
Tidal Ladder	RED (Increase)	AMBER (Increase)	GREEN	AMBER (Decrease)	RED (Decrease)	Total Levels	Individual Tidal Ladder Status:
ORIGIN To HAT	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
10.43 To 5.2	0	0	5	0	0	5	
HAT To MHWS	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
5.2 To 4.1	0	0	5	0	0	5	
MHWS To MHW	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
4.1 To 3.1	0	0	4	0	0	4	
MHW To MHWN	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
3.1 To 2.1	0	0	3	0	0	3	
MHWN To MSL	26.98%	1.59%	71.43%	0.00%	0.00%	100.00%	Status is Red Increase
2.1 To 0	17	1	45	0	0	63	
MSL To MLWN	0.00%	0.00%	59.38%	25.00%	15.63%	100.00%	Status is Amber Decrease
0 To -1.7	0	0	19	8	5	32	
MLWN To MLW	0.00%	0.00%	92.73%	7.27%	0.00%	100.00%	Status is Green
-1.7 To -2.8	0	0	51	4	0	55	
Totals	17	1	132	12	5	167	Profile T207 Spring 2016 Overall profile Status:
	10.18%	0.60%	79.04%	7.19%	2.99%	100.00%	Status is Red Increase

Fig. 10. Morphostat assessment of the T207example profile for Spring 2016.

defense), the upper and lower confidence limits converge and slight variations (within the confines of equipment accuracy) can influence results.

Most Kenfig SAC (T227-T230A) profiles eroded within the supratidal and upper intertidal areas. Despite this, 48.57% of the assessed tidal ladder zones were allocated green status, and the remaining results being amber (11.43%) and red (40%). Four zones that fell below the 99%ile confidence limit (11.43%) were associated with the area between the Origin (CPM) and HAT. In this area, the upper and lower confidence limits converge and slight variations (within the confines of equipment accuracy) can influence results.

6. Integration of Morphostat into shoreline management and adaptive environmental management plans

Globally, there is a growing acknowledged urgency to develop adaptation and mitigation measures to cope with future climate-change impacts on coastlines (Ng et al., 2015). In addition to this, climate change is expected to influence storm effects in terms of frequency, trajectory, and intensity.

In England and Wales, ICZM is implemented through the production of Shoreline Management Plans (SMP). These plans recognise that natural processes do not follow the human defined land based

Input Your Chosen "Green" Percentage Trigger Here			89.9%				Profile T215 Spring 2016 (Confidence Levels based on surveys between 1998 and 2013)
Tidal Ladder	RED (Increase)	AMBER (Increase)	GREEN	AMBER (Decrease)	RED (Decrease)	Total Levels	Individual Tidal Ladder Status:
ORIGIN To HAT	84.62%	7.69%	7.69%	0.00%	0.00%	100.00%	Status is Red Increase
10.566 To 5.2	11	1	1	0	0	13	
HAT To MHWS	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
5.2 To 4.1	0	0	10	0	0	10	
MHWS To MHW	15.00%	10.00%	75.00%	0.00%	0.00%	100.00%	Status is Red Increase
4.1 To 3.1	3	2	15	0	0	20	
MHW To MHWN	100.00%	0.00%	0.00%	0.00%	0.00%	100.00%	Status is Red Increase
3.1 To 2.1	10	0	0	0	0	10	
MHWN To MSL	0.00%	7.84%	92.16%	0.00%	0.00%	100.00%	Status is Green
2.1 To 0	0	4	47	0	0	51	
MSL To MLWN	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
0 To -1.7	0	0	97	0	0	97	
MLWN To MLW	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	Status is Green
-1.7 To -2.8	0	0	75	0	0	75	
Totals	24	7	245	0	0	276	Profile T215 Spring 2016 Overall profile Status:
	8.70%	2.54%	88.77%	0.00%	0.00%	100.00%	Status is Red Increase

Fig. 11. Morphostat assessment of the T215 example profile for Spring 2016.

Table 6
Summary of the Morphostat results for each Mumbles to Blackpill SSSI and Swansea Beach profile location.

Profile	Percentage Trigger (%)	Percentage Achieved (%)	Origin HAT	HAT MHWS	MHWS MHW	MHW MHWN	MHWN MSL	MSL MLWN	MLWN MLW	Overall Profile
T201	85.71	92.86					↓			
T202	54.05	48.65							↑	↑
T203	91.06	89.89					↓		↓	
T204	94.37	95.31					↑			
T205	89.75	86.07	↓		↑	↓			↑	↑
T206	87.50	88.66	↑		↑	↑			↑	
T207	84.62	79.04					↑	↓		↑
T208	65.15	64.89	↑	↑	↑	↑			↓	↑
T209	51.26	62.50				↑	↑	↑		
T210	59.05	50.00	↑	↑			↑	↑		↑

boundaries of administrative authorities, e.g. County Councils, but are based on natural boundaries such as sediment cells. The Welsh Government has an ICZM policy which encourages all organisations with an interest in the coastline of Wales to work together and formulate policies and plans that will lead to effective economic and sustainable management of the Welsh coastline. SMPs are a vital component of this process and provide key information to interested organisations and stakeholders. The work of Bullen was a forerunner to the first generation SMPs which were completed along the South Wales coast during 2000 and 2001 (SBCEG, 1999).

In 2010, a second generation SMP was published (SBCEG, 2010). This second-generation work (SMP2) reviewed and took account of latest available information that included climate change guidance, modifications to environmental legislation and improved understanding of flood and coastal erosion risk management to provide a long term sustainable plan for the next 100 years (SBCEG, 2010). Consequently, SMP2 considered how a section of coastline was to be managed over epochs, e.g. 25 years, 50 years and 100 years to address issues such as flooding and/or erosion. Management decisions considered predictions of climate change consequences linked to socio-economic use, e.g. coastal tourism, etc.

An extensive set of strategically placed, regularly surveyed beach profile data was not included when the assessments were compiled, possibly due to time constraints However, the need to underpin

Table 7
Summary of the Morphostat results for each Lagoon Footprint, Crymlyn Burrows SSSI, Baglan Burrows and Aberavon Sands. Profile location.

Profile	Percentage Trigger (%)	Percentage Achieved (%)	Origin HAT	HAT MHWS	MHWS MHW	MHW MHWN	MHWN MSL	MSL MLWN	MLWN MLW	Overall Profile
T213	62.84	62.01	↓				↑		↑	↑
T214	99.45	94.94	↓		↓	↑				↓
T215	89.90	88.77	↑		↑	↑				↑
T216	91.89	95.45	↑							
T217	84.74	85.71	↑	↑				↓		
T218	100.00	100.00								
T219	52.94	42.86			↓	↓	↓			↓
T220	100.00	46.58	↓	↓	↓	↓	↓			↓
T221	77.78	51.52	↓				↓			↓

Table 8
Summary of the Morphostat results for each Margam Sands and Kenfig SAC profile location.

Profile	Percentage Trigger (%)	Percentage Achieved (%)	Origin HAT	HAT MHWS	MHWS MHW	MHW MHWN	MHWN MSL	MSL MLWN	MLWN MLW	Overall Profile
T223	90.28	49.32	↓			↓	↓	↓		↓
T224	54.05	32.89	↑		↓	↓	↓	↓		↓
T224X	95.45	76.81	↓				↓			↓
T225	91.03	73.08	↓	↑			↓		↑	↑
T226	100.00	96.40	↑						↑	↑
T227	67.06	36.05		↓		↓	↓	↓		↓
T228	94.74	97.40	↓							
T229	48.00	45.45	↓	↓	↓			↑	↑	↑
T230	88.00	82.72	↓	↓	↓	↓				↓
T230A	66.67	81.01	↓	↓	↓	↓				

decisions with robust data and not just scenario planning is critical, because as argued by both Williams et al. (2016) and Parker and Ollier (2016), coastal planners require the best possible data and analyses.

Coastal practitioners also need robust and 'hands-on' approaches that simplify beach management in times of accelerated sea level rise with increasing demands on beaches to provide defence against flood and coastal erosion. There is a need to develop technologies designed to reduce the effects of climate change, (El Mrini et al., 2012; Thomas et al., 2015).

It is proposed to use Swansea Bay to construct and operate a tidal lagoon for the purpose of generating renewable energy, the first of its type in the World. This will be achieved by utilising the bay's high tidal range to generate over 400,000 MWh per annum. Such power generation is reliable and predictable, a key consideration for managing future national electricity supply from a mix of technologies (Thomas et al., 2015). Design of the Morphostat programme was inspired by the requirement for the project to develop a suitable programme for the monitoring of coastal processes as a result of construction within the intertidal zone of Swansea Bay. It soon became apparent that Morphostat could be an important addition to integrated coastal zone management. Fig. 12 shows schematically how the programme may be integrated into both shoreline Management and development plans. Baseline data and monitoring survey data are gathered and used to develop trigger levels. Morphostat assesses data and allocates colour codes to each profile. The allocated colour codes will trigger action and in this case an allocation of amber or red status would trigger an evaluation of beach volume change. If the volume changes are within historic boundaries then no further action would be required but volumes falling outside would trigger a third level assessment of supporting data. If the changes remain within the boundaries of historic change (i.e. green status) then no further action would be required and in some cases, where repeat surveys also result in green status, the monitoring regime may be adjusted or removed altogether allowing funds to be allocated to areas of concern.

7. Conclusions

It is proposed to construct a tidal lagoon that uses the natural ebb and flow of the tide to generate electricity in Swansea Bay, South Wales, the first of its type in the world. To confirm that the construction does not adversely affect the normal fluctuations of sediment in the bay, a regime was developed to monitor potential intertidal morphological change before, during and post construction. Historic beach profile data collected between 1998 and 2013, where adjusted using standard surveying functions to reflect the 2013 baseline survey, and an adaptive management strategy was developed to identify coastal changes outside normal evolutionary patterns. The resulting profile envelope that was evaluated against more recent data collected in Autumn (2015) and Spring 2016.

From these data, 'Morphostat', a novel application for monitoring beach level changes was developed to identify areas of concern, revealed from analysis against statistical parameters that is organised into tidal ladder regions. Morphostat's visual output provides a traffic light system of Red, Amber and Green that identifies relative levels of concern. This work utilised predetermined confidence limits (95%ile and 99%ile) and trigger levels determined from the autumn 2015 data. However, the user is not restricted to using these confidence limits. Exceedance of normal parameters will trigger higher levels of assessment against a predetermined management framework that would include forcing agents such as variations of in-wave height and direction, storm and surge incidence etc.

Although initially developed to monitor Swansea Bay, Morphostat can be applied elsewhere in the world for any tidal range, tidal ladder configuration and variable profile length, making it ideal as a first line tool to determine if more detailed assessments are needed. The programme can also be used to identify cross-shore oscillation (within profile change) and beach rotation (between profile change) using the tabulated results. Morphostat is therefore a useful shoreline monitoring tool for underpinning intervention/no intervention policies. It will

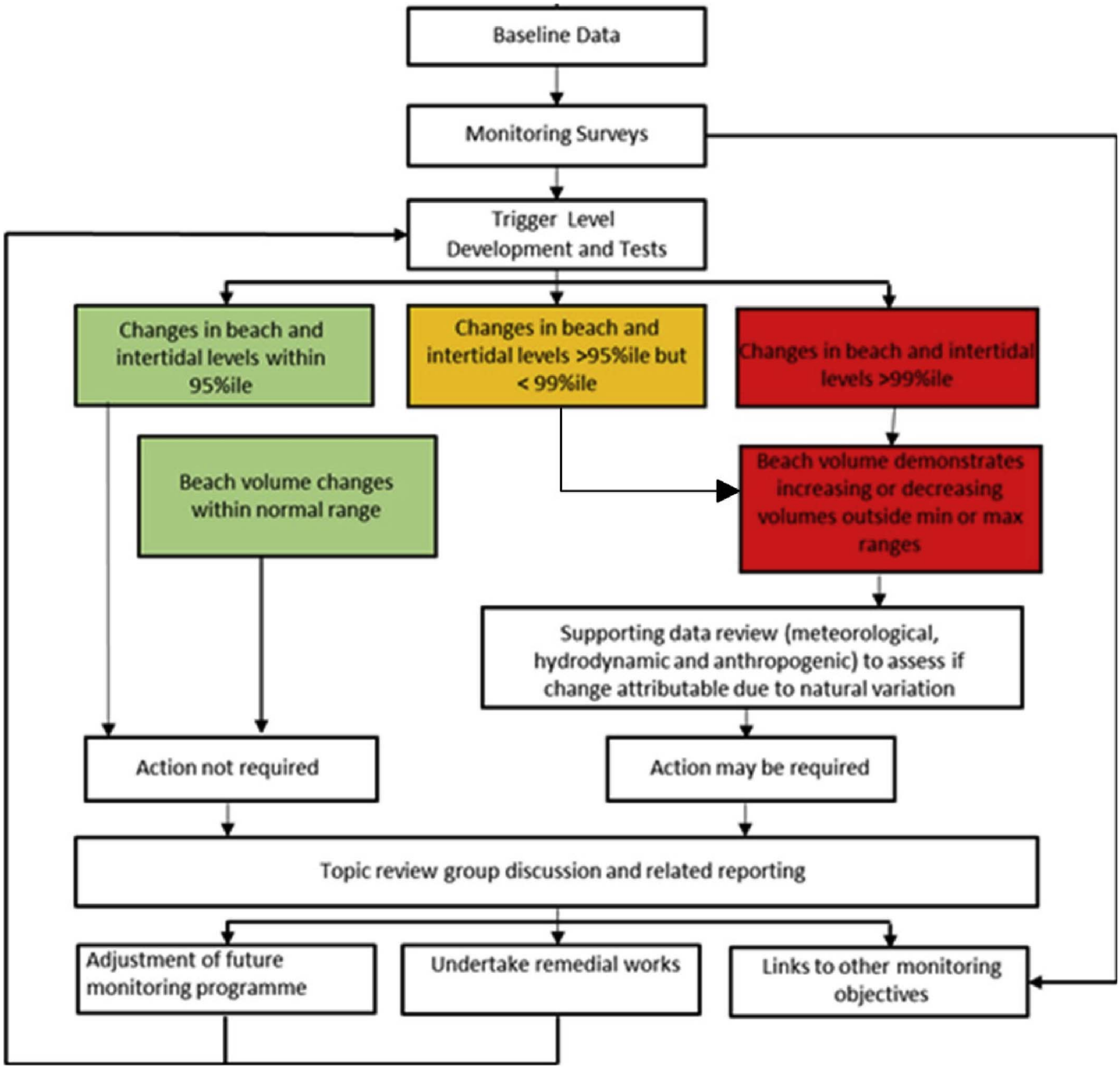


Fig. 12. a schematic detailing typical action from morphostat results.

facilitate assessment of risk, especially from climate change, where beach change can be categorised as within or outside historical trends, thereby improving future high level strategic decision making, allocation of financial resources and coastal zone management, not only in the UK but on a more global scale.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ocecoaman.2017.11.016.

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